The Impact of Nitrogen Fertilization, and Sodium Bicarbonate Application on the Growth and Productivity of Cotton under Modern Cultivation Techniques

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Abstract

This study was conducted to evaluate the efficiency of dissolved oxygen through the addition of sodium bicarbonate to drip irrigation water on nitrogen uptake and productivity of cotton (Gossypium hirsutum L.), cultivar Livzara.

The experiment was carried out during the 2025 growing season at a site affiliated with the College of Agriculture, Tikrit University, Iraq. The study was arranged according to a Randomized Complete Block Design (RCBD). Two factors were investigated. The first factor consisted of five concentrations of sodium bicarbonate (0, 9, 13, 17, and 21 mg L^{-1}), applied perpendicular to the experimental units. The second factor included two nitrogen fertilization levels using urea (46% N) at rates of 60 and 120 kg N ha^{-1}.

The results indicated that a concentration of 21 mg/L $NaHCO_3$ achieved the maximum plant height of 122.3 cm, while concentrations of 17 and 21 mg/L were significantly superior in leaf area and leaf area index (LAI), reaching 6656.1 cm^2 and 4.7, respectively. Notably, the interaction between 17 mg/L $NaHCO_3$ and 60 kg/ha N yielded the highest leaf area of 6821.8 cm^2, suggesting that enhanced root zone aeration optimizes nutrient utilization and reduces the necessity for excessive nitrogen application.

Leaf nitrogen concentration peaked at 48.4 g/kg with the 21 mg/L $NaHCO_3$ treatment, while the highest interaction value of 50.7 g/kg was observed under the combination of 21 mg/L $NaHCO_3$ and 120 kg/ha N.

Furthermore, higher bicarbonate levels (17 and 21 mg/L) significantly accelerated phenological development, reducing the time to 50% flowering to approximately 65 days and 50% boll formation to 85.8 days.

Keyword:- Nitrogen Fertilization, and Sodium Bicarbonate , Growth and Productivity

Introduction

Cotton (*Gossypium* spp.), a member of the family *Malvaceae*, is among the most economically important fiber crops worldwide, playing a central role in both agricultural sustainability and industrial development. Beyond its agronomic value, cotton underpins major textile industries, with lint fibers constituting approximately 33% of seed cotton weight. The superior fineness, strength, and whiteness of cotton fibers make it a primary raw material for global textile manufacturing (1,2). Given its

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strategic importance, optimizing cotton productivity and fiber quality remains a priority, particularly under increasing environmental constraints.

In many arid and semi-arid regions, agricultural production is increasingly challenged by water scarcity and declining water quality (3). These constraints necessitate the adoption of resource-efficient management strategies. Modern irrigation technologies, particularly drip irrigation systems, have emerged as effective tools to enhance water and nutrient use efficiency. However, one often-overlooked factor in such systems is dissolved oxygen (DO) concentration in irrigation water. Adequate oxygen availability in the rhizosphere is critical for maintaining root respiration, nutrient transport processes, and overall plant metabolic activity. Under drip irrigation, restricted soil aeration may reduce oxygen diffusion within the root zone, potentially impairing nitrogen uptake efficiency and limiting vegetative growth and yield performance(4).

The situation is further complicated in gypsiferous soils, which present unique physicochemical challenges for crop production. These soils are characterized by elevated concentrations of calcium and sulfate ions, high bulk density in certain horizons, and limited structural stability. Consequently, soil alkalinity often increases, with pH values commonly ranging between 7.5 and 8.5 (5). Such conditions may adversely affect nutrient availability, particularly nitrogen dynamics, and reduce crop performance unless appropriate management practices are implemented.

Nitrogen fertilization plays a fundamental role in regulating cotton growth, canopy development, and yield formation. Previous research (6) evaluating nitrogen application rates (0, 90, 180, 270, 360, and 450 kg N ha^{-1}) demonstrated a significant increase in Leaf Area Index (LAI) with increasing nitrogen levels, with 270 and 360 kg N ha^{-1} producing optimal canopy development at peak boll formation. Similarly, field experiments (7) reported significant improvements in vegetative growth traits with nitrogen application rates up to 300 kg N ha^{-1}, where plant height reached 124.50 cm compared to 95.20 cm in the unfertilized control. Moreover, a strong positive correlation between nitrogen rates (200–600 kg ha^{-1}) and vegetative growth parameters, including LAI and plant height, has been documented (8), underscoring the importance of adequate nitrogen supply for maximizing cotton growth potential.

Despite extensive research on nitrogen fertilization, limited attention has been given to modifying irrigation water chemistry—particularly through sodium bicarbonate supplementation—as a potential

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strategy to influence rhizosphere conditions and nutrient dynamics under gypsiferous soil environments. Given the scarcity of studies addressing this interaction, the present investigation was designed to evaluate the combined effects of gypsiferous soil conditions, nitrogen fertilization levels, and sodium bicarbonate addition to irrigation water on cotton growth performance and productivity under modern cultivation systems

Materials and Methods

Experimental Site and Soil Characteristics

The field experiment was conducted during the 2025 growing season at the College of Agriculture, Tikrit university , located north of the city of Tikrit (34.68° N, 43.46° E).

The study aimed to test the hypothesis that increasing the dissolved oxygen concentration in drip irrigation water—through the addition of sodium bicarbonate ($NaHCO_3$)—could enhance nitrogen uptake efficiency in cotton (Gossypium hirsutum L.) and improve fiber quality under nitrogen fertilization. Cotton was sown on 1 June 2025.

The soil of the experimental site is classified as gypsiferous soil, which necessitated evaluating the interaction between sodium bicarbonate–treated irrigation water and nitrogen fertilization under such soil conditions.

Experimental Design and Field Implementation

The experiment was arranged as a 2 × 5 factorial trial within a Randomized Complete Block Design (RCBD) with three replicates. Treatments were randomly distributed within each block.

Factor A: Five levels of sodium bicarbonate ($NaHCO_3$) added to irrigation water:
0, 9, 13, 17, and 21 mg L^{-1}.

These levels were systematically arranged in the field to facilitate irrigation management and prevent mixing of bicarbonate concentrations among experimental units.

Factor B: Two nitrogen fertilization levels: 60 and 120 kg N ha^{-1}.

Nitrogen treatments were randomly assigned and arranged perpendicularly within each replicate.

The land was subjected to shallow tillage for leveling purposes. A total of 30 experimental units were established, each measuring 12 m² (4 m × 3 m).

At planting, all experimental units received basal fertilization consisting of:

- Single Super Phosphate (SSP)
- Potassium sulfate (K_2SO_4)

Both were applied at a rate of 60 kg $dunum^{-1}$ to ensure adequate availability of essential macronutrients.

A drip irrigation system was used to supply water and treatment solutions. Five 200-L barrels were installed at a height of 1 m to generate sufficient water pressure.

ISSN 2072-3857

Sodium bicarbonate was added to irrigation water in alternating irrigations (one irrigation without addition followed by one with addition).

The barrels were assigned as follows:

1. Control (0 mg L^{-1})
2. 9 mg L^{-1}
3. 13 mg L^{-1}
4. 17 mg L^{-1}
5. 21 mg L^{-1}

A calibration irrigation was applied before sowing. After suitable soil drying, seeds were sown on 1 June 2025 at a depth of 3–4 cm, with 2–3 seeds per hill (late planting date). Seedling emergence occurred approximately six days after sowing (7 June 2025). Missing hills were replanted where necessary.

During the growing season, plants were attacked by cotton bollworm. Control measures were implemented using Emamectin benzoate (10% concentration). Spraying was conducted in the late afternoon to avoid photodegradation of the active ingredient and to ensure maximum absorption efficiency.

Approximately one month after emergence, thinning was performed to retain one plant per hill where multiple seedlings had emerged.

Studied traits:-

Samples from the first generation were collected on November 4, 2025, and samples from the second generation were collected on November 29, 2025. The following traits were examined

Growth characters:-

1-Plant Height (cm): The final height at the first flowering stage was measured from the base of the plant to the tip of the main stem. Measurements were taken for ten plants, from the base to the highest point of the main stem, and the average height per plant was calculated in centimeters.

2-Leaf Area Index (LAI): This represents the ratio of the total leaf area of the plant to the ground area occupied by the plant.

3-Leaf Area of Cotton Plants (cm^2): Leaf area was measured for five randomly selected plants from each experimental unit. The maximum leaf length (from the base to the tip) and maximum leaf width (at the widest point) were recorded. Leaf area was then calculated using the following formula (8)

LA= L x W x 0.77

Where:

- **LA** = Paper area (cm^2)
- **L** = Maximum length of the paper (cm)
- **W** = Maximum width of the paper (cm)
- **0.77** = Correction factor for cotton papers

4-Nitrogen Estimation: The total nitrogen content in dried leaf samples was determined using the modified Kjeldahl method, which involves wet digestion with concentrated sulfuric acid in the presence of a catalyst, followed by distillation and ammonia collection in boric acid, according to (9).

5-Days to 50% Flowering: The number of days from sowing until

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50% of the plants in each experimental unit flowered was recorded.

6-Days to 50% Nut Formation: The number of days from sowing until 50% of the plants in each experimental unit reached nut formation in the middle canopy was recorded

Statistical Analysis:-

7- Total seed cotton yield (kg ha^{-1}):- This was calculated by summing the seed cotton yield from the first and second pickings for each experimental unit and subsequently converting the yield to kilograms per hectare.

The experiment was statistically analyzed according to a Randomized Complete Block Design (RCBD) with a factorial arrangement and three replications comprised five levels of sodium bicarbonate (0, 9, 13, 17, and 21 mg·L^{-1}), while the horizontal strips included two levels of nitrogen fertilizer (urea) at 60 and 120 kg·ha^{-1}, also with three replications. Analysis of variance (ANOVA) was performed using the SAS statistical software. Means of the treatments and interactions were compared using Duncan's Multiple Range Test (D.M.R.T) at a 5% probability level(10).

Results and Discussion:-

1- Plant Height (cm)

The results of Duncan's Multiple Range Test, as presented in Table (1), revealed significant effects of sodium bicarbonate ($NaHCO_3$) concentrations in irrigation water, nitrogen fertilization levels, and their interaction on the average height of cotton plants (*Gossypium hirsutum* L.).

Data indicated a significant increase in plant height corresponding to higher concentrations of $NaHCO_3$ in the irrigation water. The concentration of **21 mg.L^{-1}** recorded the highest average plant height at **122.3 cm**, followed by the **17 mg.L^{-1}** concentration which yielded an average of **106.6 cm**. In contrast, the control treatment recorded the lowest average plant height of **72.1 cm**.

The significant increase in plant height upon $NaHCO_3$ addition may be attributed to the improvement of dissolved oxygen levels within the rhizosphere. This enhancement provides an optimal environment for root respiration and active nutrient uptake, thereby boosting photosynthetic efficiency. Consequently, this supports the synthesis of cellulose and essential materials required for cell elongation in cotton stems. These findings are consistent with **(11)**, who noted that appropriate bicarbonate levels enhance intracellular metabolism, nutrient transport, photosynthesis, and overall plant growth, explaining why the plants in this study reached maximum height compared to the control.

Regarding nitrogen fertilization, the results in Table (1) showed no significant differences in plant height. Although the **120 kg.ha^{-1}** level showed a numerical superiority with an average of **97.4 cm**

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compared to the **60 kg.ha^{-1}** level (which averaged **93.9 cm**), the difference remained statistically insignificant. This may be due to the fact that increasing nitrogen fertilization alone was insufficient to induce a significant change in the overall average height of the cotton crop, suggesting that the **60 kg.ha^{-1}** level was adequate to meet the plant's requirements. These results align with the findings of **(12)**, who observed that nitrogen fertilization promotes plant height by activating biological processes within meristematic tissues. Nitrogen supply stimulates cell elongation and increases the number of stem nodes, leading to increased stem length as a direct response to fertilizer dosage increments.

Table (1): Effect of Sodium Bicarbonate (NaHCO3) Concentrations and Nitrogen Fertilization Levels on Plant Height (cm)

Sodium Bicarbonate Concentration	Nitrogen level of 60 kg ha^{-1}	Nitrogen level of 120 kg ha^{-1}	Mean Serum Bicarbonate Concentration
Control	76.2de	68.1e	72.1e
9 mg L^{-1}	75.2e	84.1d	79.6d
13 mg L^{-1}	95.3c	100.2c	97.7c
17 mg L^{-1}	103.1bc	110.0b	106.6b
21 mg L^{-1}	120.0a	124.6a	122.3a
Mean Nitrogen Concentration	93.9a	97.4a	

*Means marked with different letters indicate the presence of statistically significant differences among them.

Table (1) shows a significant interaction between nitrogen fertilization levels and sodium bicarbonate concentration in irrigation water on cotton plant height. The interactions of (21 mg·L^{-1} $NaHCO_3$ × 120 kg·ha^{-1} N) and (21 mg·L^{-1} $NaHCO_3$ × 60 kg·ha^{-1} N) produced the highest mean plant heights, reaching 124.6 cm and 120 cm, respectively, with no significant difference between them. In contrast, the interaction of (control × 120 kg·ha^{-1} N) recorded the lowest mean plant height of 68.1 cm. This may indicate a physiological synergy between enhanced dissolved oxygen in irrigation water and nitrogen availability, where bicarbonate provided oxygen in the root zone, enabling roots to increase nitrogen uptake and assimilation, thus promoting longitudinal growth and improving the Calvin cycle efficiency. Meanwhile, nitrogen contributed to the synthesis of enzymes and proteins involved in cellulose and carbohydrate formation. This synergy led to a higher rate of meristematic cell division and elongation than either

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factor applied individually. These findings are consistent with those reported by (13), who confirmed that improving irrigation water quality by adding sodium bicarbonate enhances nitrogen uptake in cotton, thereby increasing photosynthetic efficiency.

2- **Leaf Area (cm^2)**

The results of Duncan's multiple range test presented in Table (2) indicated significant differences between sodium bicarbonate concentrations, nitrogen fertilization levels, and their interaction on the leaf area of cotton plants. It was observed that the concentrations of 17 and 21 $mg \cdot L^{-1}$ were significantly superior to the other treatments, producing the highest leaf area values of 6624.0 and 6656.1 cm^2, respectively, with no significant difference between them. In contrast, the control treatment recorded the lowest mean leaf area of 4421.5 cm^2.

This progressive increase in leaf area can be attributed to the role of sodium bicarbonate as a source of dissolved oxygen, which enhances root aerobic respiration, thereby increasing ATP production essential for the uptake and translocation of nitrogen and water to the shoots. Improved root aeration also stimulates the production of cytokinins in root apices, which are transported via the xylem to the leaves, promoting cell division and expansion, leading directly to increased leaf area. Consequently, an enlarged leaf area improves photosynthetic efficiency. These findings are consistent with those reported by (14), who confirmed that sodium bicarbonate acts as a physiological enhancer, promoting the establishment of a robust root system with high efficiency in water and nutrient absorption during the early growth stages.

Table 2. Effect of Sodium Bicarbonate Levels and Nitrogen Fertilization on Leaf Area (cm^2)

Sodium Bicarbonate Concentration	Nitrogen level of 60 $kg\ ha^{-1}$	Nitrogen level of 120 $kg\ ha^{-1}$	Mean Serum Bicarbonate Concentration
Control	4158.9e	4684.2de	4421.5c
9 $mg\ L^{-1}$	4699.7de	5288.0cd	4993.9c
13 $mg\ L^{-1}$	5725.8bc	5694.5bc	5710.1b
17 $mg\ L^{-1}$	6821.8a	6426.1ab	6624.0a
21 $mg\ L^{-1}$	6719.0a	6593.3a	6656.1a
Mean Nitrogen Concentration	5625.0a	5737.2a	

*Means marked with different letters indicate the presence of statistically significant differences among them.

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The results presented in Table 2 indicate no significant differences in the effect of nitrogen fertilization levels on the leaf area of cotton. The nitrogen fertilization level of 120 $kg \cdot ha^{-1}$ recorded a mean leaf area of 5737.2 cm^2, while the level of 60 $kg \cdot ha^{-1}$ resulted in a mean of 5625.0 cm^2. This may be attributed to the crop reaching a saturation stage at the 60 $kg \cdot ha^{-1}$ level. These findings are consistent with those reported by (15).

Results from the Duncan's multiple range test, shown in Table 2, revealed significant differences in the interaction between sodium bicarbonate concentrations and nitrogen fertilization levels on cotton leaf area. The interaction of 17 $mg \cdot L^{-1}$ sodium bicarbonate with 60 $kg \cdot ha^{-1}$ N produced the highest mean leaf area (6821.8 cm^2), followed by the interaction of 17 $mg \cdot L^{-1}$ sodium bicarbonate with 120 $kg \cdot ha^{-1}$ N (6593.3 cm^2), with no significant differences observed between them. Conversely, the control treatment with 60 $kg \cdot ha^{-1}$ N recorded the lowest mean leaf area (4158.9 cm^2). These results align with the findings of (16), which reported that strong roots transport cytokinins to the leaves, leading to increased leaf area, enhanced stomatal opening, and improved photosynthetic efficiency in cotton plants.

Furthermore, the Duncan test results indicate that leaf area was positively influenced by increasing dissolved oxygen through the application of sodium bicarbonate. The significant superiority observed at concentrations of 17 and 21 $mg \cdot L^{-1}$ can be attributed to the physiological role of dissolved oxygen in stimulating root respiration and providing the energy required for nutrient uptake. The lack of significant differences between the overall means of the two nitrogen levels (60 and 120 $kg \cdot ha^{-1}$) clearly suggests that nitrogen was not the limiting factor for vegetative growth. Instead, the growth response was largely governed by the efficiency of nutrient absorption related to root aeration and increased dissolved oxygen in the root zone. By enhancing dissolved oxygen, the plant was able to achieve maximal leaf area at the lower nitrogen level, rendering further increases in nitrogen to 120 $kg \cdot ha^{-1}$ ineffective.

3- Leaf Area Index (LAI)

The results of the Duncan's multiple range test presented in Table (3) indicate significant differences between sodium bicarbonate concentrations and nitrogen fertilization levels, as well as their interaction, on the leaf area index (LAI) of cotton. The table shows that increasing nitrogen levels from 60 to 120 $kg\ ha^{-1}$ did not result in significant differences in the overall mean LAI, with both levels having statistically equal values (4.0). This may be attributed to the sufficiency of the 60 $kg\ ha^{-1}$ nitrogen application in meeting the plant's requirements for optimal leaf area development, making further

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fertilization to 120 kg ha^{-1} unnecessary. This finding is in agreement with the observations reported by (17).

The results presented in Table (3) also indicate that sodium bicarbonate concentrations caused significant differences in the LAI of cotton. Concentrations of 17 and 21 mg L^{-1} recorded the highest overall mean LAI (4.7) with no significant difference between them, indicating that 17 mg L^{-1} is the optimal concentration for achieving maximum LAI response. In contrast, the control treatment recorded the lowest mean (3.1). The superior LAI values at higher sodium bicarbonate concentrations may be attributed to its role in improving rhizosphere aeration by increasing dissolved oxygen levels, which activates root growth and enhances nitrogen and water uptake efficiency. The attainment of a mean LAI of 4.7 at 17 and 21 mg L^{-1} also reflects the role of these treatments in stimulating endogenous hormonal activity, particularly cytokinins, which promote cell division in leaves, thereby enhancing the canopy's ability to intercept solar radiation and improving photosynthetic efficiency compared to the control treatment, which suffered from limited growth due to insufficient root aeration. These findings are consistent with those reported by (18).

Table (3): Effect of Sodium Bicarbonate Levels and Nitrogen Fertilization on Leaf Area Index

Sodium Bicarbonate Concentration	Nitrogen level of 60 kg ha^{-1}	Nitrogen level of 120 kg ha^{-1}	Mean Serum Bicarbonate Concentration
Control	2.9e	3.3de	3.1c
9 mg L^{-1}	3.3de	3.7dc	3.5c
13 mg L^{-1}	4.0bc	4.0bc	4.0b
17 mg L^{-1}	4.8a	4.5ab	4.7a
21 mg L^{-1}	4.8a	4.7a	4.7a
Mean Nitrogen Concentration	4.0a	4.0a	

*Means marked with different letters indicate the presence of statistically significant differences among them.

The results of the interaction between sodium bicarbonate and fertilization levels, as shown in Table (3), indicated significant differences in the leaf area index (LAI) of cotton. The two-way interaction results showed that the highest LAI values were recorded at the interactions of 17 mg L^{-1} bicarbonate + 60 kg ha^{-1} N and 21

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mg L^{-1} bicarbonate + 60 kg ha^{-1} N, both with a mean value of 4.8. This was followed by the interaction of 21 mg L^{-1} bicarbonate + 120 kg ha^{-1} N, which had a mean value of 4.7. In contrast, the control treatment with 60 kg ha^{-1} N exhibited the lowest mean LAI of 2.9.

These results indicate that bicarbonate concentrations of 17 and 21 mg L^{-1} represent an optimal saturation level, where any further increase in concentration does not lead to a significant enhancement in LAI. This effect may be attributed to the increase in dissolved oxygen, which enhances urease activity in the soil (particularly in the 0–20 cm layer). Urease is responsible for hydrolyzing urea and converting it into plant-available nitrogen forms, namely ammonium and carbon dioxide. Adequate nitrogen availability to the leaves directly promotes leaf area expansion by supporting chlorophyll synthesis, thereby enhancing photosynthetic efficiency. Moreover, nitrogen stimulates the synthesis of proteins and nucleic acids essential for cell division, resulting in larger leaf size.

These findings are consistent with those reported by [19], who demonstrated that increased dissolved oxygen in irrigation water led to higher populations of active soil bacteria and enhanced biochemical interactions, thereby increasing nitrate and ammonium levels in the soil.

4- Leaf Nitrogen Concentration (g·kg^{-1})

The results of the Duncan multiple range test presented in Table (4) indicate significant differences in leaf nitrogen concentration of cotton due to both sodium bicarbonate concentration and nitrogen fertilization levels, as well as their interaction. A positive correlation was observed between increasing sodium bicarbonate concentration and the measured values. The overall mean increased from 34.8 g·kg^{-1} in the control treatment to a maximum of 48.4 g·kg^{-1} at a concentration of 21 mg·L^{-1}, followed by 17 and 13 mg·L^{-1}, with means of 44.3 and 42.1 g·kg^{-1}, respectively, with no significant difference between the latter two. This improvement is attributed to the role of sodium bicarbonate addition to irrigation water as an oxygen enhancer, which increased root efficiency in nitrogen uptake. These results are consistent with the findings of [20], who reported that enriching the root zone with 10,000 ppm of oxygen can increase yield by up to 14%.

Statistical analysis in Table (4) also shows a significant effect of nitrogen fertilization levels on leaf nitrogen concentration in cotton. The highest fertilization level (120 kg·ha^{-1}) significantly outperformed the 60 kg·ha^{-1} treatment, with means of 43.0 and 40 g·kg^{-1}, respectively. This can be explained by the crucial role of nitrogen in the synthesis of amino acids and proteins, as well as its direct involvement in chlorophyll biosynthesis, enhancing the plant's capacity for cell division. These

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findings are in agreement with the results reported by[21].

Table (4): Effect of Sodium Bicarbonate Levels and Nitrogen Fertilization on Leaf Nitrogen Concentration ($g \cdot kg^{-1}$)

Sodium Bicarbonate Concentration	Nitrogen level of 60 kg ha^{-1}	Nitrogen level of 120 kg ha^{-1}	Mean Serum Bicarbonate Concentration
Control	32.4f	37.3e	34.8d
9 mg L^{-1}	38.0e	39.7de	38.8c
13 mg L^{-1}	42.4bcd	41.8cd	42.1b
17 mg L^{-1}	43.0bcd	45.5bc	44.3b
21 mg L^{-1}	46.1b	50.7a	48.4a
Mean Nitrogen Concentration	40.4b	43.0a	

*Means marked with different letters indicate the presence of statistically significant differences among them.

As shown in Table (4), there was a significant effect of the interaction between sodium bicarbonate concentrations in irrigation water and nitrogen fertilization levels on the nitrogen concentration in cotton leaves. The interaction treatment of 21 $mg \cdot L^{-1}$ sodium bicarbonate combined with 120 $kg \cdot ha^{-1}$ N significantly outperformed the other treatments, recording the highest overall mean nitrogen concentration (50.7 $g \cdot kg^{-1}$), followed by the interaction treatment of 17 $mg \cdot L^{-1}$ sodium bicarbonate with 120 $kg \cdot ha^{-1}$ N, which had an overall mean of 45.5 $g \cdot kg^{-1}$. In contrast, the lowest leaf nitrogen concentration was observed in the control treatment with 60 $kg \cdot ha^{-1}$ N, recording an overall mean of 32.4 $g \cdot kg^{-1}$.

The results in Table (4) indicate that increasing sodium bicarbonate concentrations led to a proportional increase in leaf nitrogen content at both fertilization levels. However, the response was more pronounced at the higher fertilization level of 120 $kg \cdot ha^{-1}$ N. This effect may be attributed to a synergistic activation, where increasing sodium bicarbonate concentration in the root zone enhanced the plant's nitrogen uptake capacity (particularly at 120 $kg \cdot ha^{-1}$ N). The addition of sodium bicarbonate not only improved the rhizosphere environment but also created a complementary effect that amplified active nitrogen absorption, allowing nitrogen accumulation in leaves at higher levels than all other treatments. These findings are consistent with the results reported by (19).

5- Days to 50% Flowering (days):

Results of the Duncan's multiple range test in Table (5) revealed significant effects of sodium bicarbonate concentrations in irrigation water, nitrogen fertilization levels, and their interaction on the number of days required for 50% flowering in cotton. Nitrogen levels showed a significant effect on flowering time, where increasing fertilization from 60 to 120 kg·ha^{-1} significantly accelerated flowering, with a mean of 67.1 days compared to 70.8 days at 60 kg·ha^{-1} N. This earlier flowering at higher nitrogen levels may be attributed to nitrogen's role in stimulating cytokinin synthesis in roots and its translocation to growing shoots, hormones responsible for promoting cell division and floral bud differentiation.

Increasing nitrogen to 120 kg·ha^{-1} likely induced a hormonal balance that facilitated rapid floral differentiation, reducing the time needed to reach the flowering stage. Nitrogen also plays a key role in photosynthesis as a fundamental component of chlorophyll. These results are in agreement with the findings of (22), who reported that nitrogen fertilization reduced the number of days required for the emergence of the first flower.

Table (5). Effect of Sodium Bicarbonate and Nitrogen Fertilization Levels on Days to 50% Flowering

Sodium Bicarbonate Concentration	Nitrogen level of 60 kg ha^{-1}	Nitrogen level of 120 kg ha^{-1}	Mean Serum Bicarbonate Concentration
Control	74.3a	71.0bc	72.6a
9 mg L^{-1}	73.6ab	69.0cd	71.3ab
13 mg L^{-1}	71.6abc	69.6cd	70.6b
17 mg L^{-1}	67.6d	63.0e	65.3c
21 mg L^{-1}	67.0d	63.0e	65.0c
Overall Mean Nitrogen Concentration	70.8a	67.1b	

*Means marked with different letters indicate the presence of statistically significant differences among them

As shown in Table (5), there was a significant effect of sodium bicarbonate concentrations added to irrigation water on the number of days required for 50% flowering of cotton. The control treatment recorded the longest flowering period, averaging 72.6 days, while the higher concentrations (17 and 21 mg L^{-1}) accelerated flowering to 65.3 and 65.0 days, respectively. No significant differences were observed between the 17 and 21 mg L^{-1} concentrations, indicating that 17 mg L^{-1} is the optimal concentration for achieving the

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maximum response in terms of the number of days to 50% flowering. The use of this optimal concentration (17 mg L^{-1}) significantly advanced flowering, which may be attributed to the increased dissolved oxygen resulting from sodium bicarbonate treatment. This oxygen acts as a terminal electron acceptor in the mitochondrial respiratory chain, enhancing the Krebs (TCA) cycle, which in turn increases the efficiency of ATP synthase in producing sufficient ATP molecules to support energy-demanding (endergonic) biological processes. These results are consistent with the findings of (23).

Statistical analysis in Table (5) also indicated a significant interaction between nitrogen fertilization levels and sodium bicarbonate concentrations in irrigation water on the number of days required for 50% flowering. The interaction of 120 kg ha^{-1} nitrogen with 17 and 21 mg L^{-1} sodium bicarbonate recorded the shortest flowering period of 63.0 days, which was significantly superior to all other interaction treatments, with no significant difference between the two concentrations. In comparison, the control treatment at 60 kg ha^{-1} N + control recorded the longest flowering period of 74.3 days, suggesting that the plant achieved maximum response at 17 mg L^{-1}.

From Table (5), it can be observed that the maximum advancement of flowering occurred when sodium bicarbonate was combined with 120 kg ha^{-1} nitrogen. Nitrogen serves as the structural component of amino acids and enzymes, while dissolved oxygen drives active absorption and metabolic processes. This integration accelerated growth rates and the development of floral buds, thereby reducing the number of days required for flowering. These findings are in agreement with those reported by (24).

6- Days Required for 50% Boll Formation

The results of the Duncan multiple range test presented in Table (6) show the statistical analysis of the effects of sodium bicarbonate application in irrigation water, nitrogen fertilization, and their interaction on the number of days required for 50% boll formation in cotton. The statistical analysis indicated a significant effect of nitrogen fertilization levels on the period required for 50% boll formation. The high nitrogen level (120 kg ha^{-1}) recorded a significantly shorter duration of 89.8 days compared to the low nitrogen level (60 kg ha^{-1}), which required 94.9 days.This significant acceleration in 50% boll formation under high nitrogen fertilization may be attributed to the vital role of nitrogen in enhancing physiological processes and protein synthesis necessary for the transition to the reproductive stage. This finding is consistent with the observations of [25], who reported that sufficient nitrogen availability ensures the

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plant's metabolic demands are met without delaying the growth cycle.

Table (6) also demonstrates that the addition of sodium bicarbonate caused highly significant differences in reducing the number of days required for 50% boll formation. The control treatment exhibited the longest duration, averaging 98.5 days, while this period progressively and significantly decreased with increasing sodium bicarbonate concentration. The higher concentrations (17 and 21 mg L^{-1}) achieved the best results, with the lowest overall averages of 87.5 and 85.8 days, respectively, while no significant difference was observed between the 17 and 21 mg L^{-1} treatments. The 17 mg L^{-1} concentration represents the optimal level for reducing the number of days to reach 50% boll formation, whereas the control treatment showed the longest average of 98.5 days. The acceleration in maturation may be attributed to the direct enhancement of photosynthetic performance, aligning with the findings of [16], who reported that increased dissolved oxygen in water enhances the efficiency of photosystem II and reduces intercellular CO_2 concentration

Table (6) Effect of Sodium Bicarbonate Levels and Nitrogen Fertilization on the Number of Days to 50% Nut Formation (days)

Sodium Bicarbonate Concentration	Nitrogen level of 60 kg ha^{-1}	Nitrogen level of 120 kg ha^{-1}	Mean Serum Bicarbonate Concentration
Control	101.0a	96.0b	98.5a
9 mg L^{-1}	98.3b	93.3c	95.8b
13 mg L^{-1}	96.0b	92.3cd	94.1b
17 mg L^{-1}	90.3de	84.6f	87.5c
21 mg L^{-1}	89.0e	82.6f	85.8c
Mean Nitrogen Concentration	94.9a	89.8b	

*Means marked with different letters indicate the presence of statistically significant differences among them

The statistical interaction results presented in Table (6) indicate a highly significant positive synergistic relationship between nitrogen fertilization levels and sodium bicarbonate concentrations on the trait of days required for 50% boll formation in cotton. The interaction treatment (120 kg N ha^{-1} + 21 mg L^{-1} bicarbonate) recorded the shortest mean duration of 82.6 days, followed closely by the interaction treatment (120 kg N ha^{-1} + 17 mg L^{-1} bicarbonate) with a mean of 84.6 days. Statistical analysis revealed no significant differences between these two treatments, reflecting that the plant reached physiological saturation at the 17 mg L^{-1} bicarbonate level. In

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contrast, the interaction treatment (60 kg N ha^{-1} + control) recorded the longest duration of 101.0 days. The superior performance of the higher nitrogen treatments combined with bicarbonate can be attributed to the dissolved oxygen released from bicarbonate decomposition, which alleviated root hypoxia in the drip irrigation system. This enabled the roots to utilize energy from aerobic respiration for active absorption of nitrogen ions, thereby accelerating the biosynthesis of proteins and hormones that promote boll formation. These findings are consistent with the observations reported by (16).

7- Total Cotton Boll Yield (kg·ha^{-1}):-

The studied traits presented in Table (7) revealed significant variations in total cotton boll yield under the influence of nitrogen fertilization levels, sodium bicarbonate concentrations added to irrigation water, as well as their interaction. Results indicated that increasing the nitrogen fertilization from 60 to 120 kg·ha^{-1} did not produce significant differences in boll yield. A slight, non-significant reduction in the overall mean yield was observed, with 60 kg·ha^{-1} achieving a mean yield of 3406.1 kg·ha^{-1}, which was numerically higher than the 3336.0 kg·ha^{-1} recorded at 120 kg·ha^{-1}. This finding aligns with (4), who reported that cotton’s response to nitrogen is not always linear and follows the law of diminishing returns. The lack of significant response at higher nitrogen levels may be attributed to the plant having already met its metabolic requirements at 60 kg·ha^{-1}, whereby additional nitrogen redirected carbohydrates towards dense vegetative growth at the expense of boll development , These observations are consistent with findings by (18) and (17).

Table (7): Effect of Sodium Bicarbonate Levels and Nitrogen Fertilization on Total Cotton Boll Yield

Sodium Bicarbonate Concentration	Nitrogen level of 60 kg ha^{-1}	Nitrogen level of 120 kg ha^{-1}	Mean Serum Bicarbonate Concentration
Control	2409.8d	2819.6cd	2614.7c
9 mg L^{-1}	3085.7bcd	2910.5cd	2998.1bc
13 mg L^{-1}	3318.6bcd	3219.0abc	3518.8ab
17 mg L^{-1}	4283.0a	3744.1abc	4013.6a
21 mg L^{-1}	3933.4ab	3486.6abc	3710.0a
Mean Nitrogen Concentration	3406.1a	3336.0a	

***Means marked with different letters indicate the presence of statistically significant differences**

ISSN 2072-3857

This, in turn, positively affects soil biological activity and nutrient uptake, which is consistent with the findings of (12) and (14). Furthermore, the availability of oxygen at 17 $mg \cdot L^{-1}$ improved the efficiency of applied nitrogen, as adequate aeration stimulates urease activity and soil microbial function, thereby increasing nitrogen uptake and accumulation in walnut tissues by up to 17.6%, as reported by (7).

Conclusions and Recommendations

1. Conclusions:

1. The study demonstrated that the addition of sodium bicarbonate ($NaHCO_3$) to drip irrigation water increased the concentration of dissolved oxygen in the irrigation solution. This enhancement improved root respiration and the efficiency of active nutrient uptake, particularly nitrogen, by increasing soil urease enzyme activity.
2. A concentration of 21 $mg \cdot L^{-1}$ of sodium bicarbonate resulted in the highest values of vegetative growth traits (plant height, number of branches, and leaf area). However, a concentration of 17 $mg \cdot L^{-1}$ was sufficient to reach physiological saturation for most growth traits without significant differences compared to the higher concentration.
3. The physiological integration between dissolved oxygen and moderate nitrogen fertilization accelerated the transition to the reproductive phase. The combination of 120 $kg \cdot ha^{-1}$ nitrogen and 17–21 $mg \cdot L^{-1}$ sodium bicarbonate significantly advanced flowering and nut formation compared to the control treatment.
4. Increasing the bicarbonate concentration to 21 $mg \cdot L^{-1}$ in irrigation water may direct photosynthetic products towards dense vegetative growth at the expense of total nut number, potentially causing a relative reduction in yield compared to the 17 $mg \cdot L^{-1}$ concentration.
5. The cultivar *Livzara* exhibited high genetic stability in nut weight and early maturity traits, which were not significantly affected by increased nitrogen fertilization levels but responded more prominently to the addition of sodium bicarbonate in irrigation water.

2. Recommendations:

1. Farmers can use a nitrogen fertilization level of 60 $kg \cdot ha^{-1}$ when employing techniques to increase dissolved oxygen in irrigation water via sodium bicarbonate addition, thereby reducing production costs and minimizing environmental

ISSN 2072-3857

pollution from excessive nitrogen fertilization.

2. Further studies should investigate the long-term effects of sodium bicarbonate addition on soil chemical properties.

3. Alternative methods for increasing dissolved oxygen levels in irrigation water should be tested and compared economically and in terms of productivity with sodium bicarbonate.

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